Prototyping a Wireless Sensor Node using FPGA for Mines Safety Application

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Abstract— **The sensor nodes in a wireless sensor network are normally microcontroller based which are having limited computational capability related to various applications. This paper describes the selection, specification and realization of a wireless sensor node using the field programmable gate array (FPGA) based architecture for an early detection of hazards (e.g fire and gas-leak) in mines area. The FPGAs in it's place are more efficient for complex computations in compare to microcontrollers, which is tested by implementing the adaptive algorithm for removing the noise in sensor received data in our work. Another advantage of using FPGA is also due to it's reconfigurable feature without changing the hardware itself. The node is implemented using cyclone II FPGA device present in Altera dE2 board .In this work the network comprises of 4 nodes out of which 2 are test nodes, one routing node and one base station node. An energy efficient MAC protocol is tested for transmitting the data from test node to base station node.**

Key Words— **Wireless Sensor Network (WSN), system on programmable chip (SOPC), FPGA.**

I. Introduction

The hazards happened due to un-natural gas leak and fire in a mines area raised an issue for the safety of people working in mines area, which is at a far location from a public place. However deploying a no. of sensor nodes in the mine area to make an early detect of information related to these hazardous environment and transferring the information to rescue center may avoid the drastic situation. This is possible if at all the deployed sensor nodes become a member of Wireless Sensor Network [1]. The ongoing research on communication networks made it possible to use wireless sensor network for variety of applications like fire detection, wildlife habitat monitoring, target tracking, intrusion detection. Also the development in networking technology makes the sensor nodes to form an ad-hoc network through their own contribution. The only limitation in this network is that the base station node is fixed. Other nodes can act as source as well as routing nodes [2] [3]. Each node is composed principally of one or several sensors, a processing unit and a module of communication, etc. These nodes communicate between each other according to the network topology and the existence or not of an infrastructure to forward the information to a control unit outside the zone of measure. All these features enable us to imagine an adaptive complex system built around several sensors in a wireless communication system. As far as the signal processing is concerned it is desired that an error/noise free data must be received at the final destination. To achieve this one of the adaptive algorithm can be implemented in the processing unit itself. This requires a complex computational energy efficient processing unit, which is difficult to get in classical architecture based processing unit. Also the microcontrollers show poor energy efficiency in many complex computational cases. The ASICs on the other hand are more energy efficient but are less flexible since they are application specific. This can be compensated with the use of a reconfigurable architecture based processing unit (i.e. FPGA) . In this paper, we have used the FPGA based sensor node architecture, featuring the acquisition of data related to fire (i.e. temperature) and smoke and transmission of information by routing over high data rate wireless networks such as bluetooth. Our goal is to detect and predict mines hazard promptly and accurately in order to rescue the people working in mines area. The data is transmitted from test node to base station satisfying the energy efficient MAC protocol reducing the loss of information. The remainder of this paper is organized as follows. Section II presents theory related to the network structure we used for the problem and the selection criteria in choosing a node. Section III focuses on the functional architecture of node .The last section discusses implementation details. The paper ends with a conclusion and the work which is being done in the near future at our laboratory.

II. SENSOR NETWORK ARCHITECTURE

This section is further divided into two sub-sections. In the first subsection, the network structure is discussed are discussed. Second subsection gives the selection criteria of a wireless sensor node.

A. Planned Network Structure

In our experimented network, sensor nodes collect measurement data such as temperature and density of smoke as the parameter required for determining the mines hazard rate. The proposed sensor network paradigm is shown in Fig.1.

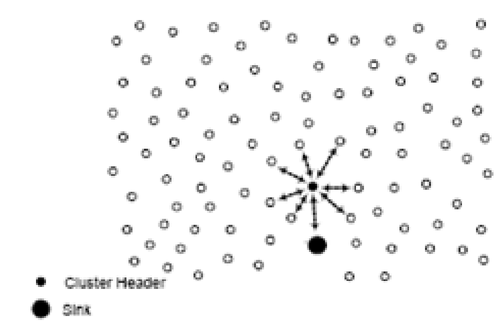

Figure 1. A wireless sensor network for mines fire detection

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As seems in fig.1 a large number of sensor nodes are densely deployed in the proposed mines area. These sensor nodes are organized into clusters so that each node has a corresponding cluster header. Sensor nodes can measure environment temperature. Every sensor node is capable of removing the noise in the data received and comparing with a standard data through a means of mathematical computation based on certain algorithms (like LMS). After making the required computation the information is sent to the base station through the corresponding cluster head. The base station after receiving the measured data related to sensor nodes can able to know the early information of fire.

B. Selection Criteria of Wireless Sensor Node

Firstly, the back bone of a wireless sensor network should be flexible, scalable, and interfaceable to analog- and digital-based sensors, removable storage and wireless. Secondly, a high degree of functionality is required to process sensor information at source to reduce the noise in the data due to environmental condition and sending the data when needed (i.e. deviation from a standard data base). This speeds communication by freeing bandwidth over the communication media and saves power to enhance the lifetime of the sensor node. In a conventional 8-bit MICA motes though the computations are possible, multiple computations take a long time. However in FPGA multiple computations can be completed within a very short time thereby we chose an FPGA [4] as the solution for the above requirements. To add more, the modules should be robust in order to able to be connected and disconnected from each other multiple times to allow experimentation. They should also be times to allow experimentation. They should also be able to withstand harsh conditions such as strong vibration when deployed in mobile sensing applications. A FPGA perfectly supports all the above requirements. To add more points to justify the selection of the node as FPGA its reconfigurabilty feature can be discussed. Despite advances in fabrication technologies, sensors generally exhibit imperfections (i.e. offset, drift, non-linearity and noise imperfections) and the magnitude of these imperfections is found to vary both from sensor to sensor and with time. Moreover, during operation, as with any other system component, sensors may develop several types of faults and fail in a variety of ways. If conventional motes are used then it would be very expensive and also very complicated to implement multiple sensor validation. So the solution is to introduce a reconfigurable digital system. Hence the solution might be a self-reconfigurable approach for providing a flexible connectionism at very low resource cost by partially reconfiguring the FPGAs (e.g. Cyclone-II).

III. Proposed Node Architecture and Design

The functional architecture and the experimental platform, is built upon the kit of development ALTERA SOPC (System One Programmable Chip).It is composed essentially by four units an acquisition unit, a treatment unit, a routing unit and a radio interface/communication unit. A basic block diagram is given below (Fig. 2).

Figure 2. Block Diagram

The detail block diagram for experimental set up is shown in fig.3.

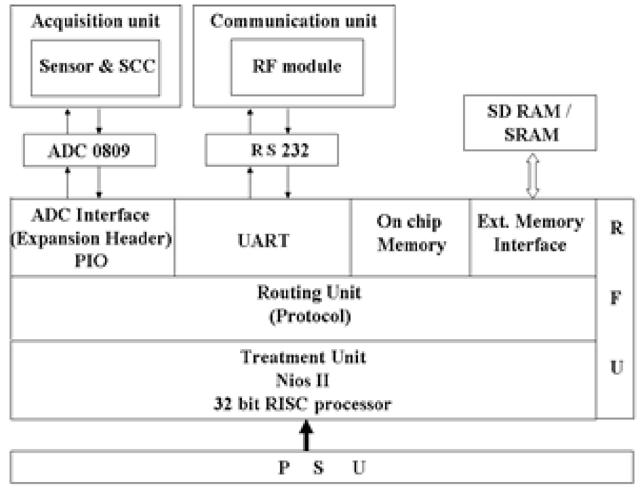

Figure 3. Block Diagram of experimental set up for the node

RFU: Reconfigurable functional unit

PSU: Power supply unit

A. Acquisition Unit

The temperature data acquisition is done by connecting a temperature sensor and the dense of smoke is detected by using smoke detector. The outputs of both of these sensors are given to their corresponding signal conditioning circuits, whose outputs are again given to ADC. The output of ADC is fed to the Altera DE2 board (FPGA kit) via the expansion header PIO available in the board itself. Periodically, the real-time temperature data and the data related to density of smoke due to fire is acquired by the corresponding sensors and given to the treatment unit.

B. Treatment Unit

The sensor data acquired is processed in the treatment unit, where the noise in the acquired data (if any) is cancelled and compared with a pre-chosen threshold value. If the value obtained is greater than threshold, then the data is sent to the base station through cluster head.

C. Routing Unit

The function of the routing unit in our experiment is to implement the basic medium access control (MAC) protocol and transmit the required data as decided by the treatment unit following an energy efficient routing protocol in wireless network. The MAC protocol is especially important in a shared medium like the air, since multiple nodes transmitting at the same time will interfere each other's communication. Since a network contains multiple independent nodes, an agreement is needed for medium access control. This agreement should be shared by all nodes in the network. Thus MAC protocol determines which node may access the medium at what time for sending its data to the base station

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through routing nodes(if any)in its path to the base station. In a wireless environment, the MAC protocol determines the state of the radio on a node sending, receiving, or sleeping. Since the radio, while listening or transmitting, uses relatively much energy, the MAC is a good place to save energy. A MAC protocol for wireless sensor networks should focus on energy usage, and ensure that radios are in sleep mode as much as possible. Important attributes of MAC Protocol to be taken care are like collision avoidance, energy efficiency, latency, throughput and scalability in node density in a network.

I. S-MAC Protocol Design

The main goal in our MAC protocol design is to reduce energy consumption, while supporting good scalability and collision avoidance [6] [7]. Our protocol tries to reduce energy consumption from all the sources that we have identified to cause energy waste, i.e., idle listening, collision, overhearing and control overhead. To achieve the design goal, we have developed the S-MAC (Sensor MAC) that consists of three major components: periodic listen and sleep, collision avoidance, and message passing.

II. Routing Protocol

We have used the Bellman Ford protocol as our routing algorithm. Here, multi-hop mechanism is used in order to route the data to the base station. Each node is assigned a node number and also a value is dynamically obtained based on the layer in which it is present which we call as the hop-count. The node with hop-count 'n' transmits its data to node with hop-count 'n-1' and this continues till the data reaches the node with hop-count '0' which is the base station.

D. Communication Unit

Bluetooth technology is a high data rate, low power consumption, low cost wireless networking protocol targeted towards automation and remote control applications. Bluetooth is expected to provide low cost and low power connectivity for equipment that needs battery life as long as several days with a high data transfer rate. The comparison between Bluetooth with WLan technologies is given in the TABLE I.

Bluetooth devices can be programmed in C/C++, sometimes require assembly language for particular time- or space-critical components. Because bluetooth devices use well-established microcontrollers, there are a number of development tools available. Hence a large amount of data can be sent to a long distance within a small time using bluetooth technology. Low-power consumption is based as much on a low-duty cycle as it is on the low-power nature of the 802.15.1 radios. Bluetooth wireless range (10-100 meters) is adequate for many applications related to WSN.

TABLE I
BLUETOOTH VS WIRELESS LAN TECHNOLOGIES

Parameter/ Technique	IEEE 802.11b & 802.11a	Bluetooth
Frequency Band and Bandwidth	IEEE 802.11b - 2.4 GHz IEEE 802.11a - 5 GHz IEEE 802.11g - 2.4 GHz	2.4 GHz
Speed	11 Mbps - 54 Mbps (Effective speed - half of rated speed)	1-2 Mbps (Effective speed - less than 50% rated speed)
Modulation Technique	Spread Spectrum OFDM	GFSK
Distance Coverage	Up to 300 feet - 802.11b Up to 60 feet - 802.11a	Up to 30 feet now- efforts to increase coverage and speed
No. of access points required	Every 200 feet - 802.11b Every 50 feet - 802.11a	Every 30 feet - 25 to 30 times number of Bluetooth access points
Cost	Much more expensive than Bluetooth	Bluetooth chips are available at less than $5

In this work we have used the PTR4500 Bluetooth module (RF module) as the communication unit, whose typical features are as shown in the TABLE II.

TABLE II
PTR4500 DETAILS

Parameter	Value
Frequency	2400 MHz-2527MHz
Channel	125
Modulation	GFSK
Maximum RF data rate	1 Mbps
RS-232 serial port data rate	57600bps, 115200 bps
Supply voltage	DC 6.0-8.0 V
Current	20-30 mA
Range (LOS, open ground):	60-70 meters

The block diagram for communication between sensor node and base cluster head node is shown in fig. 4.

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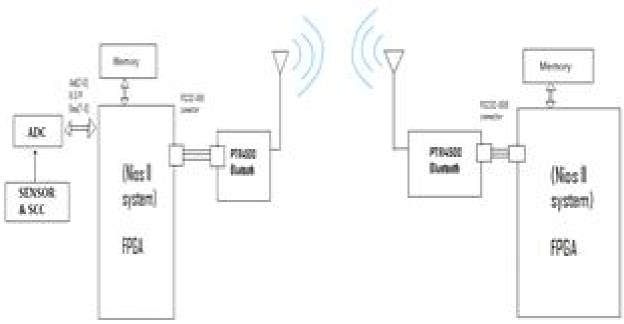

Figure 4. Communication between sensor node and cluster head node

The prototype of interfacing of bluetooth module with Altera DE2 board using RS 232 is shown in fig. 5.

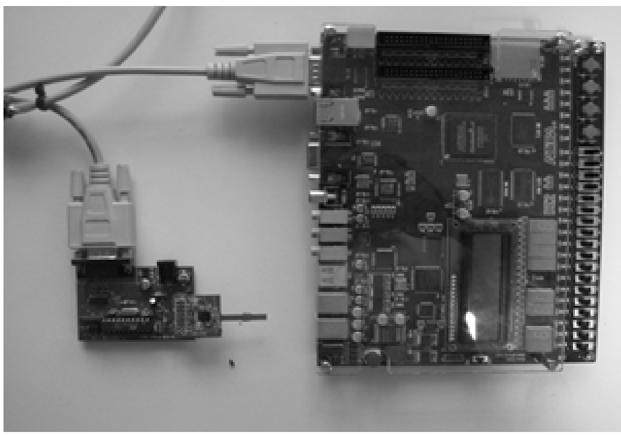

Figure 5. Interfacing FPGA with Bluetooth module

IV. HARDWARE IMPLEMENTATION

The node in the experimented sensor network is realized using Altera DE2 board. The node uses NIOS II soft core processor as a part of FPGA device to act as the processor in the treatment unit of the said node architecture. The FPGA uses SRAM cells to store configuration data related to architecture. The system configuration is carried out using the SOPC builder tool. A part of the SOPC builder is shown in fig.6.The Quartus II software automatically generates VHDL or BDF file related to the system configuration so as to be used while execution. For testing of the configured system using FPGA through a PC, the device is configured in passive configuration mode- JTAG (Joint test action group) mode. The Quartus II software generates *.sof* files that can be downloaded using USB Blaster Cable for JTAG configuration.

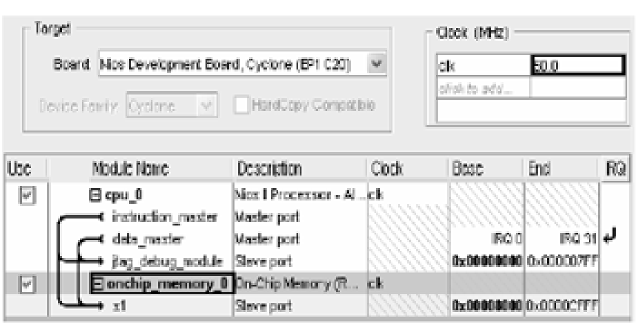

Figure 6. SOPC builder showing the presence of NIOS processor and memory

After the configuration is being over necessary peripheral interfacing (such as acquisition unit & communication unit) is made and tested. For perfect operation of interfacing related IP cores must to be included to the configuration data (e.g. ADC interface through PIO core & UART core for interfacing the RF module as suggested in fig.3).The block diagram for the practical temperature sensor interface is shown in fig.7.

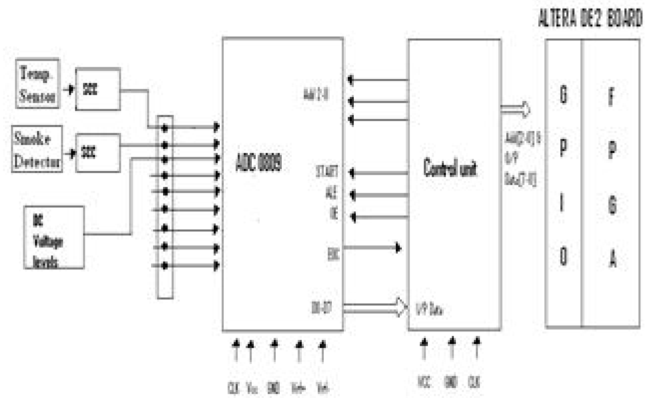

Figure 7. Sensor interface system

After the successful interfacing of ADC and blue tooth module to the FPGA kit the sensor data is read from ADC output, through the NIOS II processor using the necessary C/C++ commands. The received data is processed through the noise canceller designed using the logic cells of FPGA. The noise caneceller functions as per the adaptive algorithm (LMS) written in VHDL whose corresponding block schematic is shown in fig.8.Then the data is compared with the pre-defined threshold value, and if found greater, then transmitted using the routing and MAC protocol. The last phase of the implementation includes the testing of protocols (.i.e. Routing & MAC) as a function of routing unit as suggested in fig. 3. Once the configuration and testing is over, the proposed nodes deployed to the network for practical application.

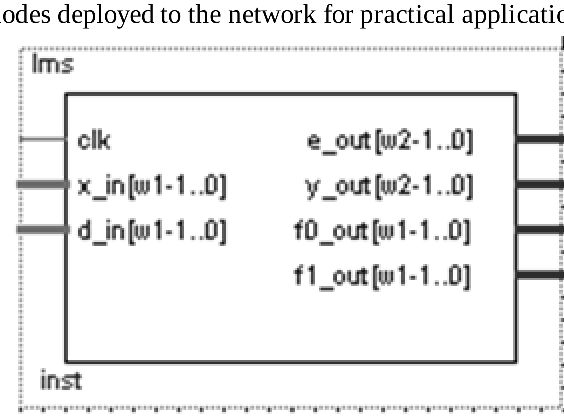

Figure 8. Block schematic of adaptive noise canceller

V. RESULTS AND DISCUSSION

In a WSN based application it is well known that the nodes are limited in energy (i.e. Battery powered).Thus it is required that the node should spare a small amount of energy out of it's total available energy for it's computational as well as transmission/reception job. In fact the energy consumed is very less in computation as compared to transmission/ reception. Hence in our experiment we have focused more on

DOI: 01.IJEPE.02.02.157

decreasing the transmission/reception energy. We achieved this following the two processes pointed below.

(i) To reduce the transmission energy the data received from sensors are transmitted only in case there is a considerable amount of change with respect to the base data not always.

(ii) Energy efficient protocols are used for the transmission of data form the node to the base station using the shortest path.

In our first part of the experiment the sensor data is acquired for different temperatures and the temperature values are verified with a standard temperature measuring device (thermometer). The data acquired is as given in the TABLE III.

TABLE III
ADC OUTPUT FOR DIFFERENT TEMPERATURES

Sensor I/P (Temperature in° C)	Output of SCC (in Volt)	Output of ADC (in Hex)
25	1.13	5A
28	1.30	5C
30	1.35	5D
32	1.45	5F
34	1.53	61

Next to the temperature data acquisition, the smoke on the basis of different densities are sensed through the smoke detector and tested for acceptance through human nose. The data acquired is as given in the TABLE IV.

TABLE IV
ADC OUTPUT FOR DIFFERENT DENSE SMOKES

Sensor I/P	Output of SCC (in Volt)	Output of ADC (in Hex)
No smoke	0.03	00
Low dense smoke	1.15	5A
Moderate dense smoke	1.40	5E
High dense smoke	1.75	73

The data read by NIOS II form ADC for 25 samples for a period of one hour is shown in fig. 9.

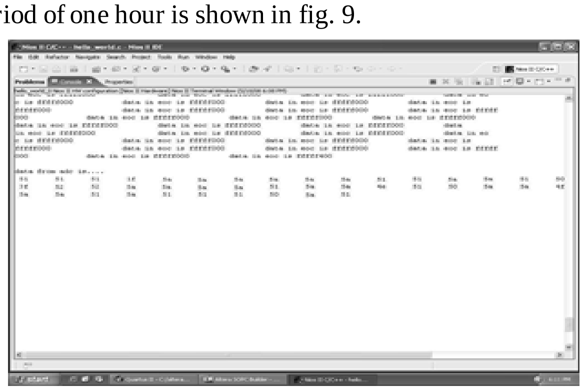

Figure 9. Data read by NIOS II

To have accuracy both the sensor datas are received alternatively and sent to the noise canceller up to 25 values. The VHDL simulated output of the noise canceller in .vwf form is shown below in fig.10.

Figure 10. Simulated output of Adaptive noise canceller

The average of 25 values is calcuted in the NIOS II processor. The average is compared with the threshold value (i.e.55 in our experiment), if found greater then transmitted.In the simillar fashion the smoke density data has been transmitted. The simulated output shown in fig. 11 indicates the receiving of data from nodes by the base station node through the routing node. In our experiment we have considered 4 nodes with address 0 through 3(node 0 being the base station, node 1 being the routing node, node 2 and 3 being the station node). For the efficient use of MAC when one node starts transmitting the data other sensing node remains in sleep mode.

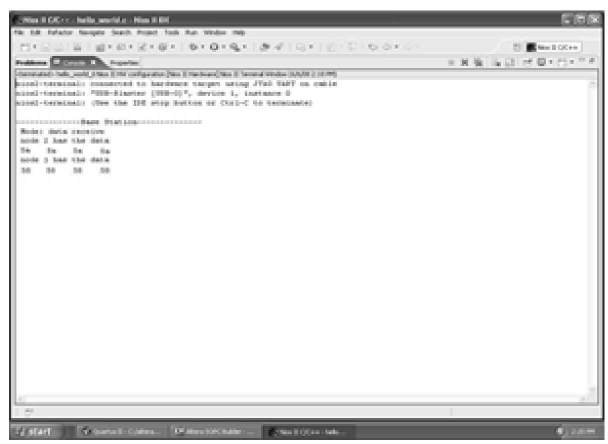

Figure 11. Data received by base station node

Since the application is WSN based, it is also important to consider energy efficiency of individual nodes as far as the life of the node is considered for a long period. Hence we have transmitted the average temperature value to the base station by using energy efficient protocol (LEACH). The energy consumption or energy saving due to compression for a node is taken into consideration as our second experiment. The energy consumption details are taken from LEACH (Low Energy Adaptive Cluster Hierarchy) [8].The details are given in TABLE V.

DOI: 01.IJEPE.02.02.157

TABLE V
ENERGY CONSUMPTION DETAILS

Operation	Energy Dissipated
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Transmitter Amplifier (E_{amp})	100 pJ/bit/m^2

The approximate energy consumption details based on the theoretical values has been computed for transmission of 8-bit data and shown in TABLE VI.

TABLE VI
APPROXIMATE ENERGY CONSUMPTION DETAILS

No. of bits	Approx. Energy consumed -TX if d=10m (In nJ)	Approx. Energy consumed-RX (In nJ)
8	480	400

CONCLUSIONS

The data acquisition related to different temperature and different dense smokes is done successfully and the obtained data is treated using the adaptive algorithm technique. The functionality of nodes are well tested with a set up of 4 nodes, where two nodes are used to sense the data, one acts as routing node and another one as base station node. The data after computation is transmitted from the two field nodes with the successful testing of energy efficient MAC protocol (i.e. S-MAC in our test) to the base station through the routing node. Since each node can act as routing node shortest path algorithm is also used to send the data from a field node to base station node. Finally, since the computation is made (i.e. adaptive algorithm and comparison with a pre-defined data base) is done using the same FPGA device, the reconfigurable feature is partially tested. The same intelligent system can be extended in other high-end applications like driver-drowsy system, video capturing applications and so on.

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